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Computational modelling of wear and the effective frictional behaviour of elastoplastic tools

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Micro Abstract
Surfaces of sheet bulk metal forming tools are often structured, either to favour material flow in desired directions, or to reduce the process forces. During continuous operation, the surface structures of the tools suffer from material wear which in turn effects the frictional behaviour which is responsible for the favoured flow directions. In order to capture both effects numerically, this contribution presents a framework for the modelling of wear and the effective frictional behaviour of elastoplastic tools.

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Introduction

Recently, a 2d-framework for the computational modelling of sliding wear of elastoplastic forming tools has been published in [2] which has now been extended to a general 3d-framework. This framework consists of a Python programme which interacts as a pre- and post-processor with the commercial finite element solver Abaqus/Standard, [5]. Thereby, the pre-processing part of the Python programme sets up a meso-scale contact problem of the elastoplastic structured tool as well as the elastoplastic workpiece where Coulomb friction is assumed. Subsequently, the sliding contact problem is solved by Abaqus/Standard. Finally, the post-processing part of the Python programme computes wear on the basis of the obtained finite element results with the help of the classic Archard wear relation, [1], in form of a dissipation rate density formulation, [4], at two different time scales. The slow time scale, the t-scale, is the time scale at which wear evolves and the fast time scale, the τ-scale, is the time scale at which the deformation of the considered bodies in contact is observed, [4]. Hence, the Python pre- and post-processor acts on the slow time scale, whereas Abaqus/Standard solves the contact problem at the fast time scale. Furthermore, the meso-scale contact problem is considered as a periodic cell which represents a representative contact problem according to [6]. Here, a scale separation from a process (macro-)scale, where structured forming tools are used, is assmued. Besides the computation of wear, the post-processing part of the Python programme determines the resulting effective Coulomb friction coefficient, [3]. Due to the deformation of the two bodies in contact, the effective homogenised Coulomb friction coefficient differs from the Coulomb friction coefficient used in the meso-scale contact simulation.

1 Governing equations

In this work, two deformable elastoplastic bodies $\mathcal{B}^1$ and $\mathcal{B}^2$ are considered at the meso-scale in a geometrically exact finite element framework. These bodies undergo wear due to frictional contact. In order to model the wear process, two separated time scales t and τ are introduced, [4]. At time scale t, the wear evolves slowly compared to the fast time scale τ of the deformation problem. Differently from the framework proposed in [4], only two configurations, the reference configuration as well as the current configuration, are considered in this contribution. As a consequence, at each discrete point in time at the t-scale, the wear increment is applied to the reference configurations of the two bodies of the representative contact problem. Hence, the bodies have time dependent reference configurations $\mathcal{B}_0^i(t, \tau = \tau_0)$ as well as the respective current configurations $\mathcal{B}_\tau^i(t, \tau > \tau_0)$. For both bodies, the respective nonlinear deformation map $\boldsymbol{\varphi}^i(\boldsymbol{X}^i, \tau)$ is determined in order to express the current placements by

$$\boldsymbol{x}^i\Big|_{t=\text{fixed}} = \boldsymbol{\varphi}^i(\boldsymbol{X}^i, \tau)\Big|_{t=\text{fixed}} , \quad \tau \in [\tau_0, \tau_{\text{end}}] , \quad t \in [t_0, t_{\text{end}}] . \tag{1}$$

At any point of the contact surface $\partial\mathcal{B}_0^*$, the contact tractions

$$\boldsymbol{t}^* = \boldsymbol{P} \cdot \boldsymbol{N}^* \tag{2}$$

as well as the contact velocity $\dot{\boldsymbol{\varphi}}^*$ are evaluated. In the above expression, $\boldsymbol{P}$ is the Piola stress tensor and $\boldsymbol{N}^*$ is the referential contact surface normal vector. In order to evaluate the wear rate, sliding velocity $\dot{\boldsymbol{\varphi}}_{\text{T}}^*$ – which is tangential to the current contact surface with the surface normal $\boldsymbol{n}^*$ – must be determined. Hence, $\dot{\boldsymbol{\varphi}}_{\text{T}}^* \cdot \boldsymbol{n}^* = 0$ must hold. With this at hand, the spatial wear rate $v_{\text{w}}^i = k^i\, \boldsymbol{t}^* \cdot \dot{\boldsymbol{\varphi}}_{\text{T}}^*$ is evaluated, where k^i is the the spatial wear coefficient. Subsequently, the spatial wear rate is transformed to the material wear rate

$$V_{\text{w}}^i = \frac{\boldsymbol{n}^i \cdot \text{cof}(\boldsymbol{F}^i) \cdot \boldsymbol{N}^i}{\det(\boldsymbol{F}^i)}\, v_{\text{w}}^i = \frac{\boldsymbol{n}^i \cdot \text{cof}(\boldsymbol{F}^i) \cdot \boldsymbol{N}^i}{\det(\boldsymbol{F}^i)}\, k^i\, \boldsymbol{t}^* \cdot \dot{\boldsymbol{\varphi}}_{\text{T}}^* \tag{3}$$

as outlined in [4]. Finally, the average wear rate at the $t-$scale is calculated by

$$\Delta V_{\text{w}}^i = \int_t^{t+\Delta\tau} V_{\text{w}}^i \,\text{d}\tau , \quad \text{on} \quad \partial\mathcal{B}_0^* , \tag{4}$$

which is then upscaled by a parameter $M \gg 1$ such that $\Delta t = M\,\Delta\tau$ in order to obtain the updated reference configuration for the next point in time $t_{n+1} = t_n + \Delta t$, i.e.

$$\boldsymbol{X}_{n+1}^i = \boldsymbol{X}_n^i - M\,\Delta V_{\text{w}}^i\, \boldsymbol{N}^{*i} , \quad \text{on} \quad \partial\mathcal{B}_0^* . \tag{5}$$

Furthermore, the homogenised effective coefficient of friction is obtained via

$$\bar{\mu} = \frac{1}{\Delta\tau} \int_{\tau_1}^{\tau_2} \frac{F_{\text{T}}(\tau)}{F_{\text{N}}} \,\text{d}\tau , \tag{6}$$

as proposed in [3]. Within the finite element framework, the above mentioned integration point quantities must be extrapolated to the element nodes via suitable algorithms. Details regarding the implementation can be found in [2].

2 Numerical results

The wear modelling framework is applied to determine the evolution of wear of structured surfaces at the meso-scale. In [2], differently parameterised sinusoidal surface structures are investigated regarding their wear evolution as well as regarding the evolution of the respective effective coefficient of friction. With the extensions presented in this contribution at hand, it is possible to model the wear of 3-dimensional surface structures. Therefore, the systematic investigation of 2-dimensional sinusoidal surface structures is expanded to 3 dimensions. In Fig. 1, an exemplary 3-dimensional structure is depicted where the sinusoidal surface topology is rotated by 60°. A block with a plain surface which represents the workpiece is pressed against and slid alongside the structured part which represents the tool in analogy to the 2d-examples

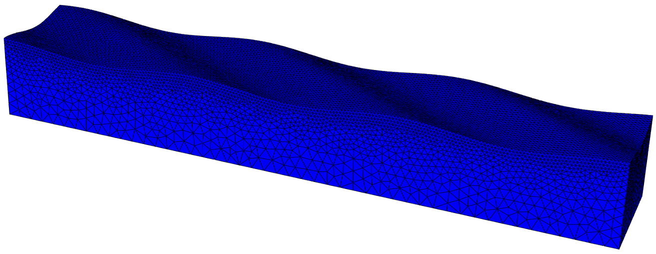

Figure 1. 3-dimensional structured tool with a sinusoidal surface structure which is rotated by $60°$. Length, width, wave length, amplitude.

in [2]. Thus, the top face of the upper block is subjected to a pressure load of 35 MPa, whereas the bottom face is the contact zone. The free faces of the upper block are subjected to periodic boundary conditions. The top face of the lower structured tool is the contact zone and the bottom face is completely constrained via homogeneous Dirichlet boundary conditions. The free faces at its sides are left free, and the error made occuring following this inconsistency can be accepted. The simulation keeps track of the horizontal reaction force of the structured tool. The material parameters of the two bodies are taken from [2]. For each increment $\Delta\tau$ at the $\tau-$scale, the upscaling parameter M is determined, and the upscaled wear is applied in the post-processing step of the Python programme. The sum of all M parameters is the number of total passovers of the workpiece over the structured tool. In Fig. 2, the worn surface of the tool, cf. Fig. 1, after 36.000 passovers is depicted. Here, Fig. 2 (a) shows the von Mises stress, whereas Fig. 2 (b) is a plot of the equivalent plastic strain. A closer look at the formerly sinusoidal edge reveals the wear since the topmost zone is flattened after 36.000 passovers. In Fig. 3, the homogenised coefficient of friction $\bar{\mu}$ is normalised to the meso-scale Coulomb coefficient of friction μ and is plotted versus the number of total passovers. It shows that the structure influences the effective coefficient of friction. Furthermore, it is obvious that flattening of the structure due to wear leads to decreasing structural resistance and, as a consequence, lowers the homogenised coefficient of friction.

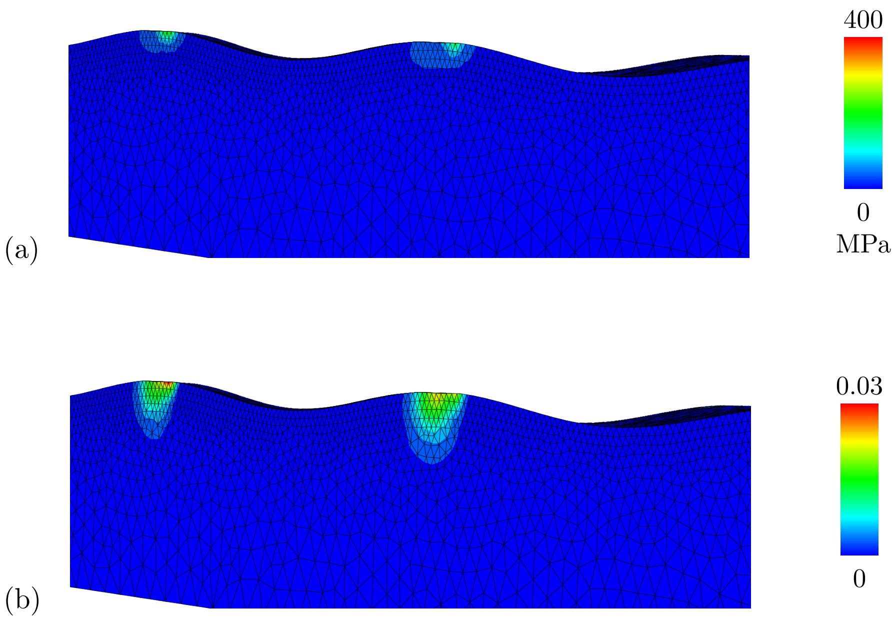

Figure 2. (a) Von Mises stress and (b) equivalent plastic strain plots of the structured tool, cf. Fig. 1, after 36.000 pass-overs.

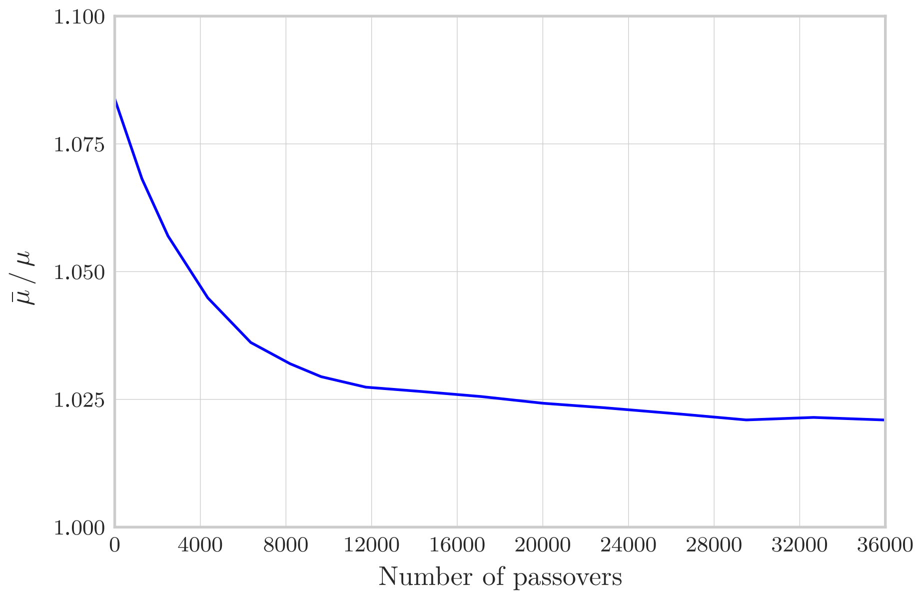

Figure 3. The homogenised coefficient of friction is normalised $\bar{\mu}\,/\,\mu$ and plotted vs. the number of passovers.

Conclusions

In this contribution, the extension of a 2d-wear-simulation-framework is further extended to 3d. The combined simulation tool consists of a Python pre- and post-processor for the commercial finite element solver Abaqus/Standard. Contact boundary value problems are pre-processed by the Python code, solved by Abaqus/Standard and finally post-processed by the Python programme which applies the calculated wear increment to the considered bodies and delivers the effective coefficient of friction as a homogenised result. The non-invasive structure of the Python programme makes the framework suitable for the application with any finite element programme that is capable of contact formulations.

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